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A new method of spatial filtering for Schlieren visualization of ultrasound wave fields

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Abstract

Schlieren visualization of ultrasound wave fields is a relative fast and inexpensive way to analyze different transducer characteristics. The spatial filtering in the Fourier plane offers an interesting possibility for image processing. Especially for comparatively low-frequency ultrasound wave fields around 1 MHz the requirements on the quality of the optical components and the filtering in the Fourier plane increases because of decreasing distances between the different orders and the difficulty to influence each of them separately. In this contribution a new method is introduced to realize the necessary spatial filtering. A Digital Micromirror Device (DMD) is used as a adjustable filter for the amplitudes in the Fourier plane without influencing the phase information simultaneously. Using different filters (e.g. knife-edge cutoff or low-pass filter) sequentially and applying methods of information fusion the quality of the sound field visualization can be improved significantly. With this setup the interpretation of different phenomena (e.g. sound interaction with solid boundaries) is possible. The experimental setup and first interesting results will be presented.

Keywords: Digital Micromirror Device; Fourier optics; Schlieren imaging; Ultrasound

1. Introduction

There are several methods to measure and visualize ultrasound wave fields, for example using a hydrophone for point wise analysis or registering the displacement of a thin membrane with a laser vibrometer. All of them have two important disadvantages. First of all, they are invasive methods which influence the wave field to be measured. Furthermore, the measurement is very time-consuming. Because of this, the sensibility of environmental conditions like the temperature is very high.

An alternative way to visualize an ultrasound wave field is the Schlieren method [4], [9]. With this optical setup it is possible to analyze sound fields very fast because the whole area of interest can be observed simultaneously and non-invasive.

An important component of a Schlieren measurement setup is the filter in the Fourier plane, which performs the real time manipulation of the spatial frequency distribution. Some usual filters are described in [1] and [3]. The

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elementary knife-edge, which blocks half of the spatial frequency plane, was introduced by Toepler. Other simple filters are described in the literature like low-pass spatial filter (bright-field Schlieren imaging), high-pass filter [7] (opaque circular spot-mask, dark-field Schlieren imaging) or a band-pass filter as a combination of them [8]. More complex ones are graded filters or selective phase-manipulating objects [1]. E.K Reichel for example uses a LC-display to manipulate the phase information of the transmitted light for example [6].

This contribution will focus on the possibility to change an amplitude modulating filter during the measurement of an ultrasound wave field. The different resulting visualizations are combined for an improved picture of the pressure field. In contrast to many medical applications with the use of high-frequency ultrasound fields [5], comparatively low-frequency ultrasound wave fields around 1 MHz will be analyzed.

2. Theory of Fourier optics

For the mathematical descriptions the coordinates shown in Fig.1 are used. The lens is defined in the x,y -plane and the back focal plane (Fourier plane) is in the u,v -plane.

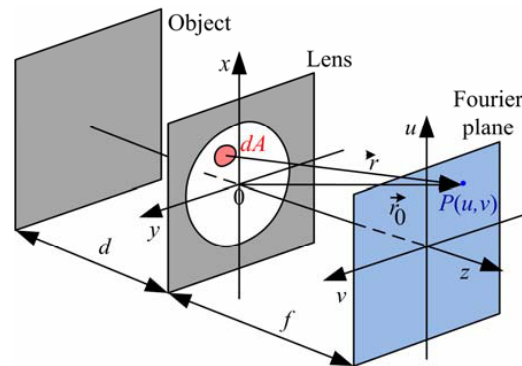


Fig.1 Definition of coordinates used for the mathematical description

The input is assumed to be uniformly illuminated by a normally incident, monochromatic plane wave. The phase modulating ultrasound wave field in front of the lens represents the object. The starting point for the mathematical description is the Fresnel diffraction integral shown in (1), where k is the wave number, r is the distance from a point of the lens to the marked point P (2), E_0 is the wave field intensity distribution at $z=0$ and λ is the wavelength of the incident monochromatic light. [2], [10]

$$E(u, v, z) = \frac{1}{j\lambda} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_0 \frac{e^{jkr}}{r} \frac{1}{2} (1 + \cos(\vec{e}_z, \vec{r})) dx dy \quad (1)$$

$$r = \sqrt{z^2 + (u-x)^2 + (v-y)^2} \quad (2)$$

At this point, the Fresnel approximations (3) and (4) are introduced. The first can be used if the angle between the acoustical axis and the direction of the vector \vec{r} to the point P is small enough. The second one is an approximation for the distance r and is based on the binominal expansion for the exact value shown in (2).

$$\cos(\vec{e}_z, \vec{r}) \approx 1 \quad (3)$$

$$r \approx z + \frac{(u-x)^2}{2z} + \frac{(v-y)^2}{2z} \quad (4)$$

With these approximations and the definition of the two-dimensional Fourier integral (5) the Fresnel diffraction integral (1) can be written as shown in (6).

$$\begin{aligned} F(f_x, f_y) &= \mathcal{F}\{f(x, y)\} \\ &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) e^{-j2\pi(f_x x + f_y y)} dx dy \end{aligned} \quad (5)$$

$$E(u, v, z) = A(u, v, z) \mathcal{F}\left\{E_0 e^{j\frac{\pi}{2z}(x^2 + y^2)}\right\} \quad (6)$$

where $A(u, v, z)$ is introduced as a abbreviation for the expression shown in (7).

$$A(u, v, z) = \frac{e^{jkz} e^{j\frac{k}{2z}(u^2 + v^2)}}{j\lambda z} \quad (7)$$

For great distances and with the use of the transfer function of the thin lens (8), it follows (9), where a quadratic phase factor can be seen.

$$t_{\text{lens}} = e^{-j\frac{k}{2f}(x^2 + y^2)} \quad (8)$$

$$E(u, v, f) = \frac{e^{jkf} e^{j\frac{k}{2f}(1-\frac{d}{f})(u^2 + v^2)}}{j\lambda f} \mathcal{F}\{E_0\} \quad (9)$$

For the special case $d = f$ and $z = f$ shown in Fig.1 the influence of the phase factor disappears and the exact Fourier transform relation remains. For this case, the manipulation in the Fourier plane influences the real spatial frequency distribution.

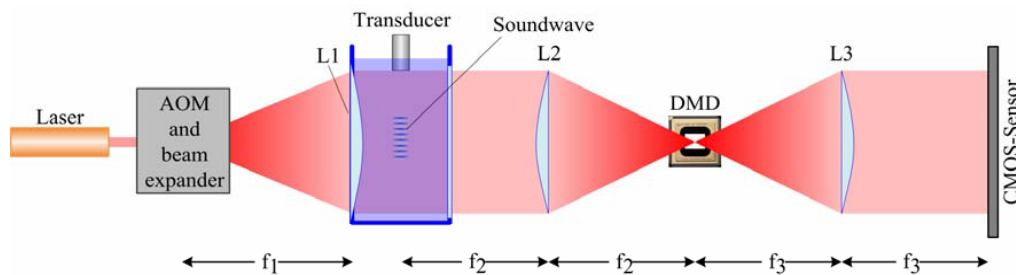


Fig.2 Experimental setup

3. Experimental setup

An overview of the experimental setup is shown in Fig.2. The main components are described in the following sections.

3.1. Light source

A HeNe-laser with a wavelength of 632 nm is used as the light source. To visualize transient ultrasound wave fields, it is necessary to expose the propagating field at the same position in the test chamber repeatedly. The short

laser pulses have to be triggered with the input signal of the transducer to freeze the relative position. Switching the laser itself is leading to a very slow repetition rate and an acousto-optic modulator (AOM) is used instead as shown in Fig.3. With activated AOM the first order of diffraction can be used as a fast switched laser light source. The pulsed laser beam is focused onto a $30\text{ }\mu\text{m}$ pin hole afterwards to get a very small point light source and consequently a highly parallel beam in the test chamber.

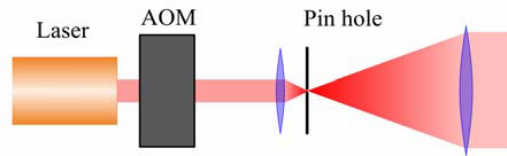


Fig.3 Pulsed point light source

3.2. Further optical components

The expanded laser beam is parallelized with a 150 mm diameter plano-convex lens L1 with a focal length of 330 mm whose air facing side is coated for the specific wavelength. This lens is mounted in one side of the test chamber to reduce the count of phase changes for better optical quality. The opposite site of the chamber is build of a coated precision BK7 window. With these components disturbing reflections can be minimized. The distance between the investigated object in the test chamber and the second lens L2 is chosen as f_2 because of the conditions mentioned in the section B. This lens has a focal length of 1000 mm to ensure the ability to manipulate the different spatial frequencies separately without overlapping.

3.3. Filter realization and image capturing

The Digital Micromirror Device (DMD) is adjusted in the back focal plane of the lens L2. It consists of 1024×768 micromirrors with a pitch of approximately $13\text{ }\mu\text{m}$ (see Fig.4).

This DMD is often used as a part of a typical DLP beamer. It is controlled by a VGA-signal of a personal computer. If a pixel is set to black the incident light is reflected to an absorber and don't contribute to the output signal. If a pixel is set to white, the angle of the micromirror approximately changes about 12 degree and the related spatial frequency in the Fourier plane is reflected to the CMOS-sensor. By changing the positions of the active pixels on the Chip an exact adjustment of the filter can be achieved. With this device it is possible to apply different filters manipulating the spatial frequency distribution in the Fourier plane.

The lens L3 focuses the visualization of the ultrasound field on a CMOS chip. This sensor is a part of a conventional digital camera with (3456×2304) pixels, a chip size of $(22,2 \times 14,8)\text{ mm}^2$ and a resolution of 12 bit. In addition the High Dynamic Range (HDR) imaging technique is applied to increase the resolution up to 32 bit by combining several different captures at changing exposure times to one resulting high resolution image. With this visualization the measured intensity can be analyzed with high accuracy without clipping over-exposed areas.

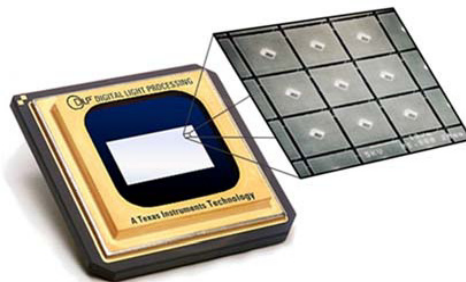


Fig.4 Digital Micromirror Device (DMD) from Texas Instruments

4. Results

4.1. Simulation

To verify the experimental results it is helpful to compare them with a theoretical model of the setup. For this a simulation program for applying different filters is developed. With this program the influence of different filters on the resulting visualization can be calculated. In addition disturbing influences like vignetting effect caused by a finite extend of the lens aperture can be analyzed. Some exemplary results are shown in Fig.5. It can be seen that different filters lead to different visualization results and therefore include different information on the ultrasound wave field.

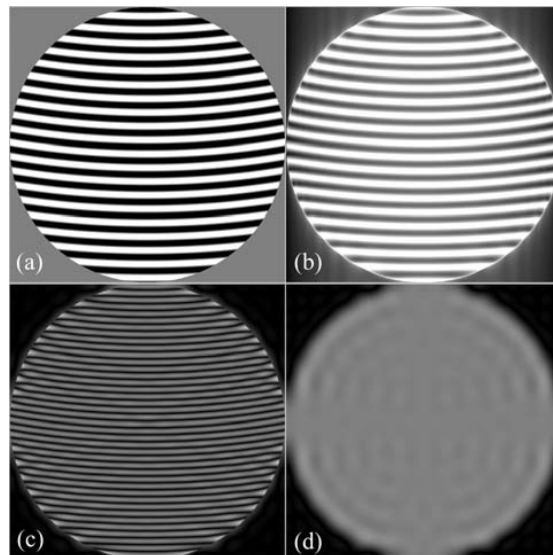


Fig.5 Simulation results: (a) example of phase changing object, filter results: (b) knife edge, (c) high-pass, (d) low-pass

4.2. Experimental results

The following experimental results illustrate the ultrasound wave field caused by a Panametrics V303 transducer with a center frequency of 1 MHz. A sinus-burst with 8 cycles is used to investigate the transient ultrasound propagation.

4.2.1. Fourier plane

To visualize the Fourier plane, the filter device is temporarily displaced by the imaging device. The resulting image is shown in Fig.6. The direction of the investigated ultrasound wave field can be derived from the spatial frequency distribution. In this example the sound field is propagating mainly in the vertical direction. The resulting intensities have very different orders of magnitude, so the captured high resolution information can only be displayed as a mapped 8 bit version which causes some clipping artifacts.

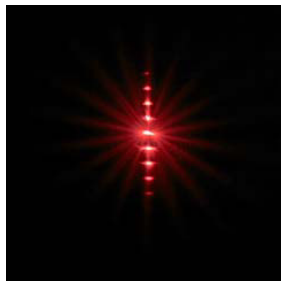


Fig.6 Enlarged image of the resulting Fourier plane mapped to 8 bit resolution

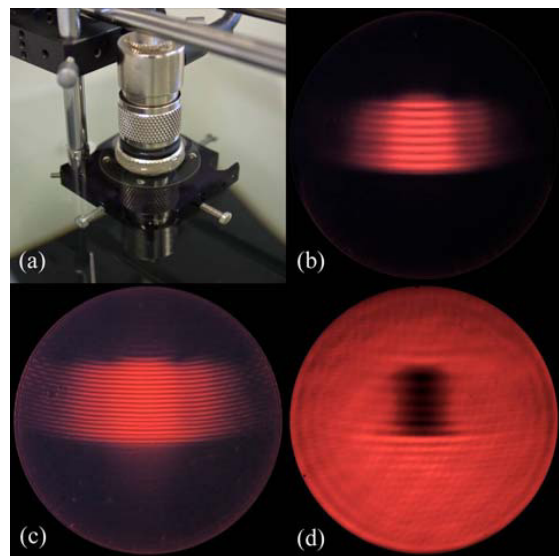


Fig.7 (a) Panametrics V303 in the test chamber, filter results with (b) knife edge, (c) high-pass, (d) low-pass filter

4.2.2. Different filters

In Fig.7 several visualization results of different manipulations in the Fourier plane (Fig.6) are shown. The underlying filters are generated with the DMD to achieve alternative visualizations.

One main advantage of the described filter generation is the possibility of combining different visualization results to an improved image without changing the main setup. An example for this information fusion is shown in Fig.8 where two measurement results with a simple knife edge at two perpendicular angles are combined. Because results from filters of this kind are depending on their orientation, one single capture is not sufficient to recognize the whole ultrasound wave field. With the combination of more than two measurements, the image quality can be improved furthermore.

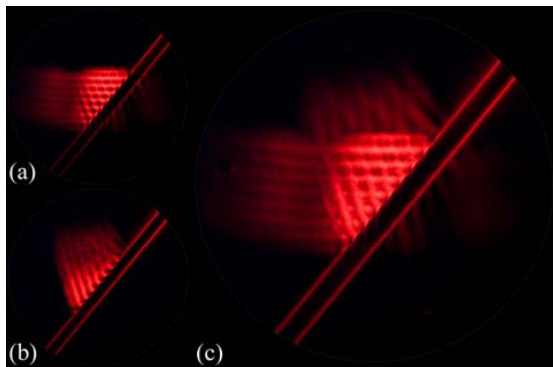


Fig.8 Combination (c) of different knife-edge measurement results (a) and (b) (reflection on a thin steel plate)

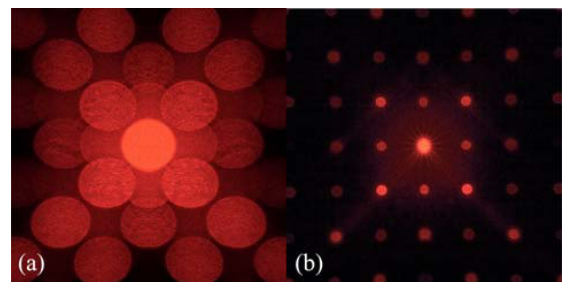


Fig.9 Influence of the pixel structure on the visualization: (a) overlapping areas and (b) separated areas

4.2.3. Influence of pixel structure on visualization

An important characteristic of the micromirror device is the periodic arrangement of the single mirrors which can be seen in Fig.4. This periodicity influences the visualization result of the ultrasound wave field. By replacing the sensor with a large-scale projection screen, this influence becomes visible (Fig.9). If the area of interest is chosen to large, the repeated visualizations influence each other and the ultrasound wave field is not displayed correctly.

So the periodicity limits the test area and only areas whose visualization results don't overlap can be analyzed. The usable diameter therefore depends on the focal length of L2, the wavelength and the pixel pitch of the DMD.

5. Conclusion and outlook

With the introduced Schlieren measurement setup it is possible to get visualization results of an ultrasound wave field in a short time. The main application for this setup is the verification of the development status within optimization routines applied to new ultrasound transducers. Important parameters of them are optimized within a finite element simulation (FEM) and should be verified from time to time. Further research will focus on the implementation of new filter characteristics to improve the visualization results and to take advantage of the possibility to change the filter while measuring. With the use of tomographic algorithms the three-dimensional pressure field shall be reconstructed to visualize unsymmetrical testing objects.

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